Insights on the performance of the Blue Nile gauging stations with special emphasize on Khartoum gauging station

Eng. Amira Mekawi[1], Eng. Hiba Amin[2]
[1] Assistant Prof., The Hydraulics Research Center - Ministry of Water Resources, Irrigation and Electricity, Sudan, E-mail: hrs_amira@hotmail.com
[1] Research Engineer, The Hydraulics Research Center - Ministry of Water Resources, Irrigation and Electricity, Sudan, E-mail: hiba.ameen@yahoo.com

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Abstract

Accurate determination of flow discharges is essential as it ensures good quality of dependant hydrologic or hydraulic studies. Although the Blue Nile system is intensively studied, its reach in Sudan (~ 700 km) lacks detailed studies for its hydrological network. Khartoum is one of the important stations on the Blue Nile in Sudan. During flood time, close observations of the flood levels at the Sudanese capital Khartoum is very vital and it is highly linked with those monitored at Eddeim on the Ethiopian/Sudanese border. In fact, Khartoum can reflect the Blue Nile total yield at Eddeim, taking into consideration the lateral flows, irrigation abstractions, losses, etc... This work highlights the performance of the major gauging sites on the Blue Nile with special emphasize on Khartoum to deliver accurate flow discharges over the period 1965-2015.

Investigating of Khartoum's ratings, water balance computations between neighbouring sites, and simulation of flow records using RIBASIM software (10-day time step) have derived concrete conclusions on Khartoum performance. It was concluded that the gauging stations at downstream Roseires and Sennar dams are of good performance. For Khartoum, the observed annual yields were overestimated by 5.3%. RIBASIM simulations showed that the observed flows were underestimated and overestimated by about 9% and 8% versus simulated flows in years of low and high flows, respectively. Hence, the reliability of Khartoum flows are limited and their accuracy is subjected to the quality of ratings and the lack of discharge measurements throughout the year.

Key words**:** Blue Nile in Sudan, Khartoum gauging site, discharge reliability

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1. INTRODUCTION

The gauging of the Nile River in Sudan started in 1869 after which the network of hydrological stations has gradually developed. Existence of hydrological monitoring basically aims to provide timely and adequate information for monitoring the regime of the Nile and its tributaries, assessment of water use for demand management, flood management and flood damage mitigation, reservoir operation and measuring reservoir evaporation losses.

Maintaining environmental flow among others. Figure 1 presents the historic hydrometric network. This figure can be read with Annex 1. The hydrological data comprises river water levels (H) and discharge measurements (Q). The Blue Nile system in Sudan consists of the Blue Nile main river and its two major tributaries Dinder and Rahad Rivers. All of them originate from the Ethiopian Highlands.

The hydrometric monitoring network of the system is considered good as it satisfies most of the required standard criteria for the purpose of assessing the flow at the key points viz: near the frontiers, above and below the confluence of joining tributaries, above and below the storage reservoirs, at principal points of water abstractions and at sites of potential water resources development (SWECO, 2014).

In the Blue Nile, measurements of water levels and discharges are carried out at a number of key stations. The yield from the Ethiopian catchment that enters Sudan is controlled by Eddeim gauging site. The joint operation of Roseires and Sennar dams and the close observations of the water levels at the upstream and downstream provide high quality information. Moreover, considerable number of gauging sites exists on the system for water levels measurements only.

Khartoum gauging station is located at the Blue Nile mouth. It is a key site as it controls the total yield of the Blue Nile before the confluence with the White Nile to form the Main Nile which flows downstream to Egypt. During flood time, close observations of the flood levels at the Sudanese capital Khartoum is of utmost important.

At Khartoum, the record started in 1904, and is a combination of flows from two sites: high flows are measured at Khartoum itself, while low flows are measured at Soba which is about 25 km upstream. Each site has its own staff gauge and separate rating curves are developed (Sutcliffe, 1999). Two sites are used because neither is suitable at both high and low flows. At Khartoum, low flow velocities are so small that measurement becomes inaccurate and the site suffers from backwater from the White Nile, but at high flows the bridge provides a good control and backwater is not a major problem as the Blue Nile flows are very much greater than those in the White Nile at this time. In contrast, Soba provides a better control than Khartoum at low flows, but at high flows velocities become so great that they are difficult to be measured. There is negligible inflow or abstraction between the two sites and the time delay is not of great significance, Figure 2 gives the locations of the two adjacent stations.

Historically, there was an adequate number of discharge measurements for this station; 40 a year at Soba and 30 at Khartoum, but declining to about 20 at each site since 1977. Investigation on the Blue Nile system has always drawn the attention of researchers as it represents more than 60% of the Nile River total yield. Also, many irrigation schemes and proposed development projects rely on its water resources. Hence, existence of hydrological networking of good performance can contribute a lot to the need for quantified water flows. This paper aims to focus on certain issues concerning the performance of the major gauging sites on the Blue Nile with special emphasis on Khartoum. It aims specifically to check the reliability of the information as delivered by this vital location.

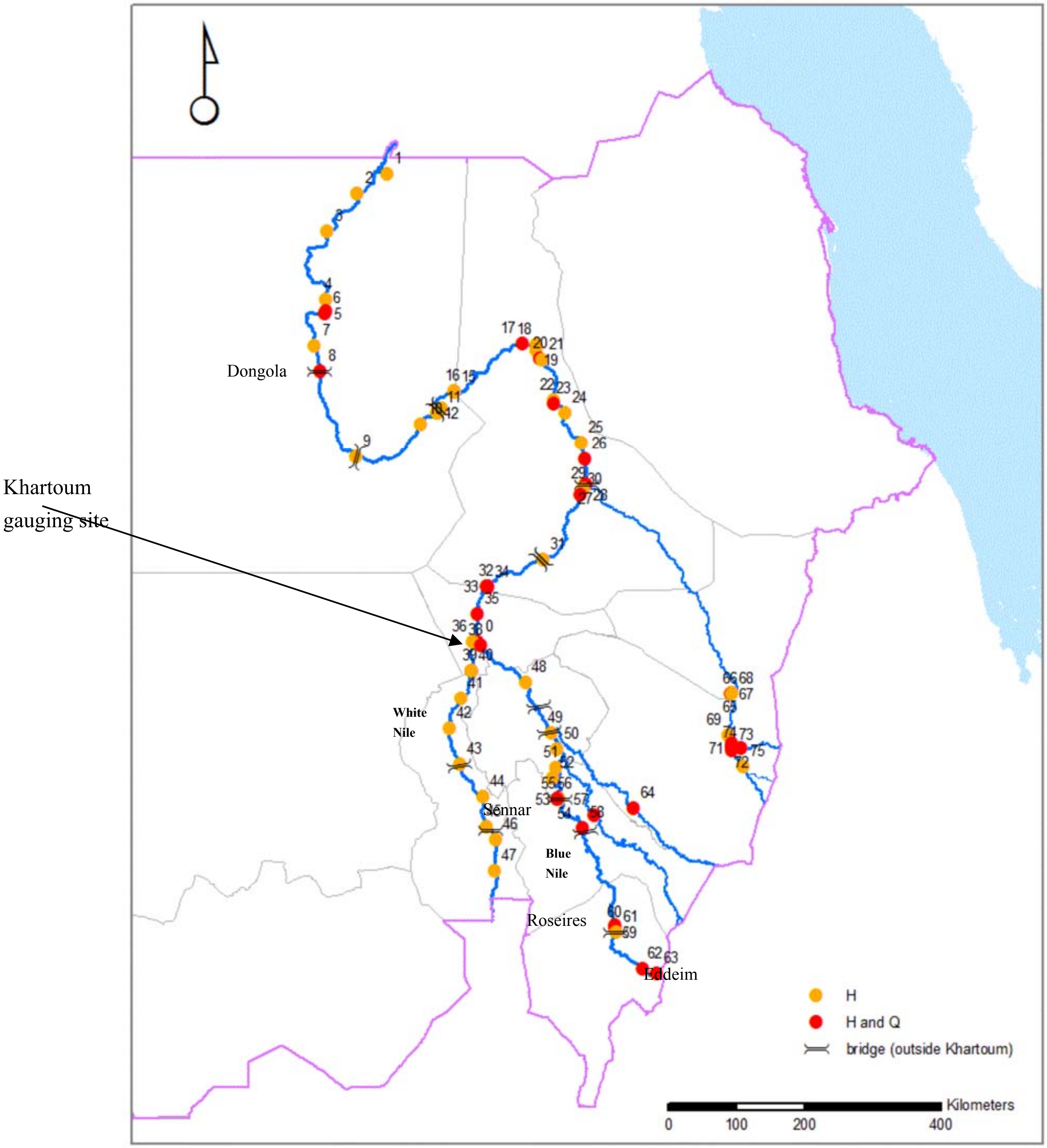


Figure 1: Historic hydrometric network in Sudan, SWECO International (2014)

Figure 2: Locations of Khartoum and Soba stations

2. METHODOLOGY

Detection of inconsistency or non homogeneity in the observation series commonly employs statistical tests, either parametric or non-parametric. The choice between the two families of tests is based on the expected distribution of the data involved. If data is normally distributed, parametric tests are preferred. Hydrological data is often not normally distributed; hence the non parametric test will be used, (Dahmen, 1990).

The non parametric test includes change point test; test for absence of trend; test for stability of variance; and test for stability of mean. Spell-stat software (version 1.7.5.46 B, 2005) is applied in this work. This software was developed by Jorge A. GUZMAN and Ma. Librada CHU Universidad Industrial de Santander, Bucaramanga – Colombia. Spell-stat is a time series statistical analysis software developed to provide an easy way to evaluate homogeneity, consistency and independence of hydrological data (Agor, 2005).

Collected information of Khartoum gauging stations over the period 1965-2015 was subjected to intensive analysis considering the following points:

1. Determination of the basic statistical parameters using Spell-stat software
2. Testing the annual yields and the 10-day discharges time series of Khartoum using the non-parametric tests of Spell-stat software
3. Investigation of constructed rating curves to highlight the impacts of the morphological changes within the station location.
4. Check the water balance of the reach Sennar – Khartoum.

In addition, flows on 10-day time step of Eddeim, downstream Roseires and downstream Sennar gauging stations over the period under investigation were also collected.

On the other side, River Basin Simulation Model (RIBASIM) was used to simulate the flows at major gauging sites at downstream of Roseires and Sennar dams and Khartoum. RIBASIM is a software developed by Deltares-Delft and it is based on a water balance approach. The software was launched with all necessary hydrological inputs (flow records at Eddeim, irrigation demand and losses from Roseires and Sennar reservoirs and river reaches in addition to reservoirs' operation rules). Figure 3 shows the schematization of the Blue Nile reach in Sudan using RIBASIM.

RIBASIM offers various hydrologic channel and reservoir routing procedure, such as: Manning formula, the flow - water level relation, the 2-layered, multi-segmented, Muskingum formula, the Puls method and the Laurenson non-linear "lag and route" method. In this work, Muskingum method was used for flow routing. As it is widely applied in river flow routing, its simplicity, and due to availability of all required data (initial storage, travel time, etc…) in comparison with other routing methods.

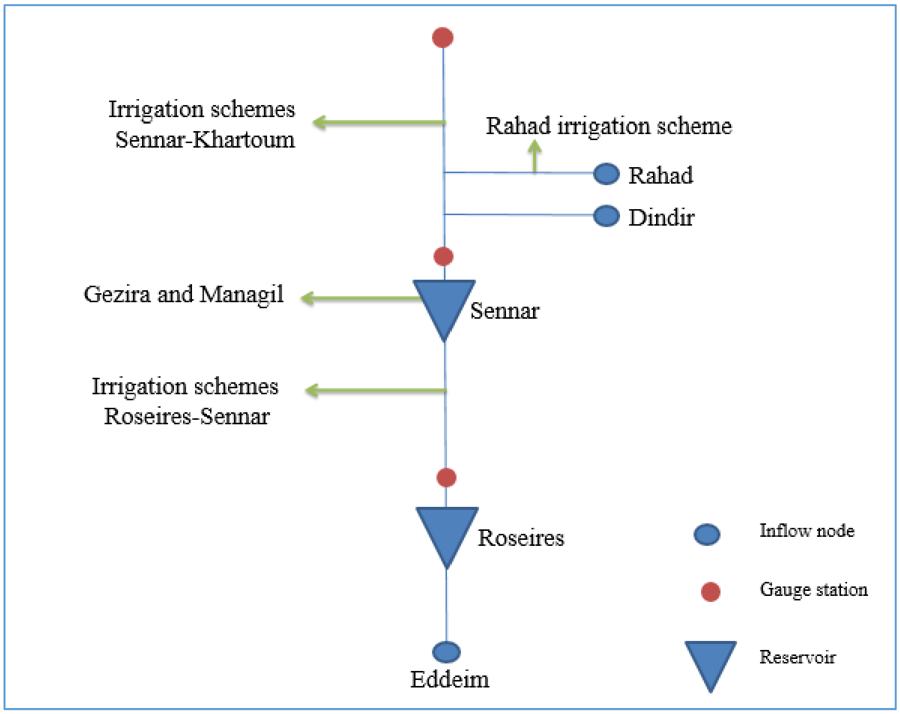


Figure 3: Schematization of the Blue Nile reach in Sudan using RIBASIM

3. RESULTS AND DISCUSSIONS

Basic information

Table 1 gives basic information about the locations of major gauging sites on the Blue Nile. Available data type consists of daily water levels and corresponding calculated discharges.

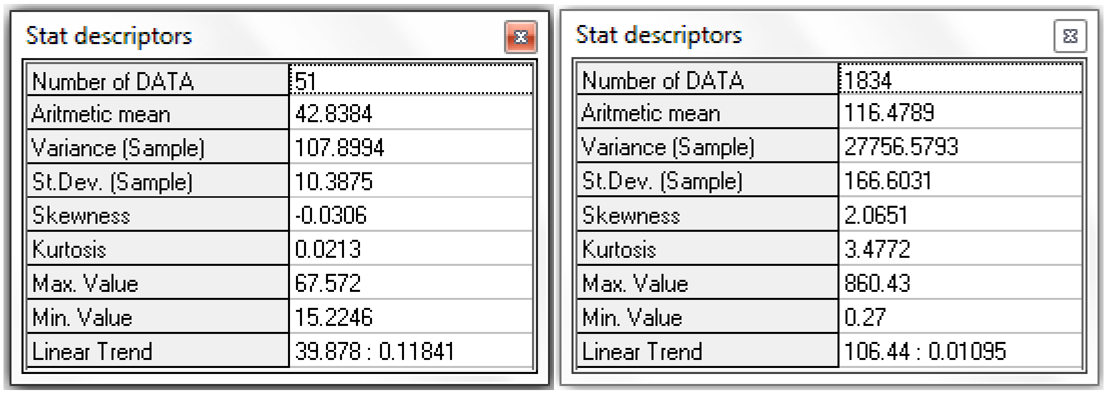
Table 1: Basic information on the Blue Nile gauging sites

Gauging Site	Date of Erection	Latitude X°Y΄N	Longitude X°Ý E	Gauge Zero (m)	Chainage from Dongola (km)	Data Type	Period Covered
Eddeim	1962	11 14	34 59	481.2	1796	H, Q	1965-2015
D/S Roseires dam	1966	11 50	34 23	-	1683	H, Q	1972-2015
D/S Sennar dam	1925	13 33	33 38	403.0	1415	H, Q	1972-2015
Khartoum	1904	15 36	32 31	363	1063	H, Q	1965-2015

Spell-Stat results

Using Spell-stat software, the time series of annual yields and 10-day average discharges at Khartoum over the period 1965-2015 was tested. Preliminary statistics were determined as in Table 2 below.

Table 2: Basic statistical records of Khartoum: for annual yields (on the left) and for the average discharges (on the right)



Stat descriptors

Number of DATA	51
Aritmetic mean	42.8384
Variance (Sample)	107.8994
St.Dev. (Sample)	10.3875
Skewness	-0.0306
Kurtosis	0.0213
Max. Value	67.572
Min. Value	15.2246
Linear Trend	39.878 : 0.11841

Stat descriptors

Number of DATA	1834
Aritmetic mean	116.4789
Variance (Sample)	27756.5793
St.Dev. (Sample)	166.6031
Skewness	2.0651
Kurtosis	3.4772
Max. Value	860.43
Min. Value	0.27
Linear Trend	106.44 : 0.01095

Quick check of the time series of the annual yields of Khartoum station has shown that 67.6 (year 1988) and 15.2 (year 1984) BCM were recorded as the highest and lowest yields respectively. A figure amounts to 42.8 BCM is considered as a long term average yield. The annual yields at Khartoum are presented by Figure 4.

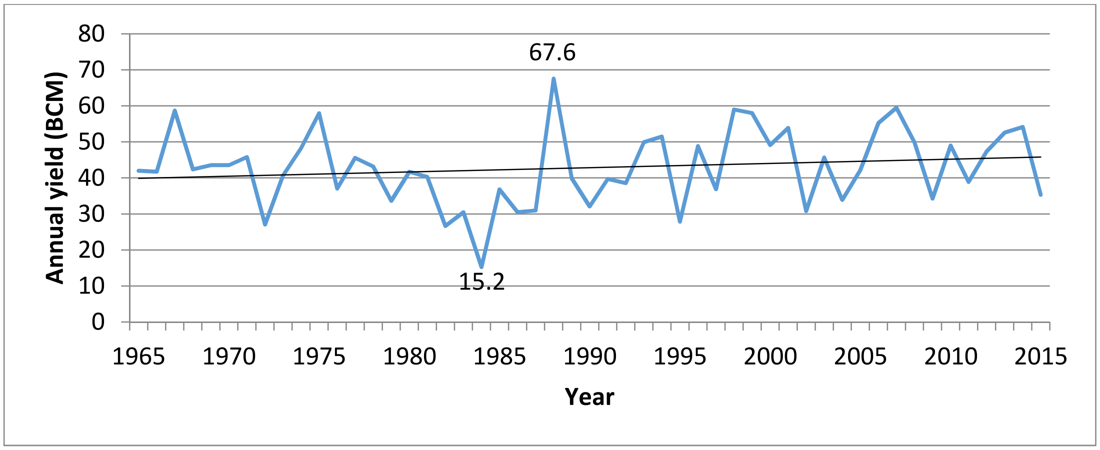


Figure 4: Time series of the annual yields at Khartoum

On the other side, flood warning levels at Khartoum have not been updated recently and the adopted records by the Sudanese Ministry of Water Resources, Irrigation and Electricity are as in Table 3 below.

Table 3: Flood threshold at Khartoum station

Alert	Critical	Flooding
15 m	16 m	16.5 m

Source: Werner, 2010.

For the change point test, a probability greater than 0.8 is considered as a change point. This is valid for both the annual yields time series and the 10-day discharges time series. Also, tests of stability of variance (F-Test) and stability of the mean (T-Test) have shown that the presence of jump is significant for the 10-day discharges time series while it was not significant for the annual yields time series.
Spearman Rank Correlation (Rs) has shown that the trend is not significant for the annual yields time series while it was significant for the 10-day average discharges of Khartoum.

Flow hydrograph establishment and generated rating curves (Q Vs H)

As basic requirements for any gauging site, a long term flow hydrograph is established using 10-day average discharges as shown by Figure 5. From this figure, one can clearly recognize that the flood peak usually reaches Khartoum within ten days (on average) after its occurrence at Eddeim in mid August.

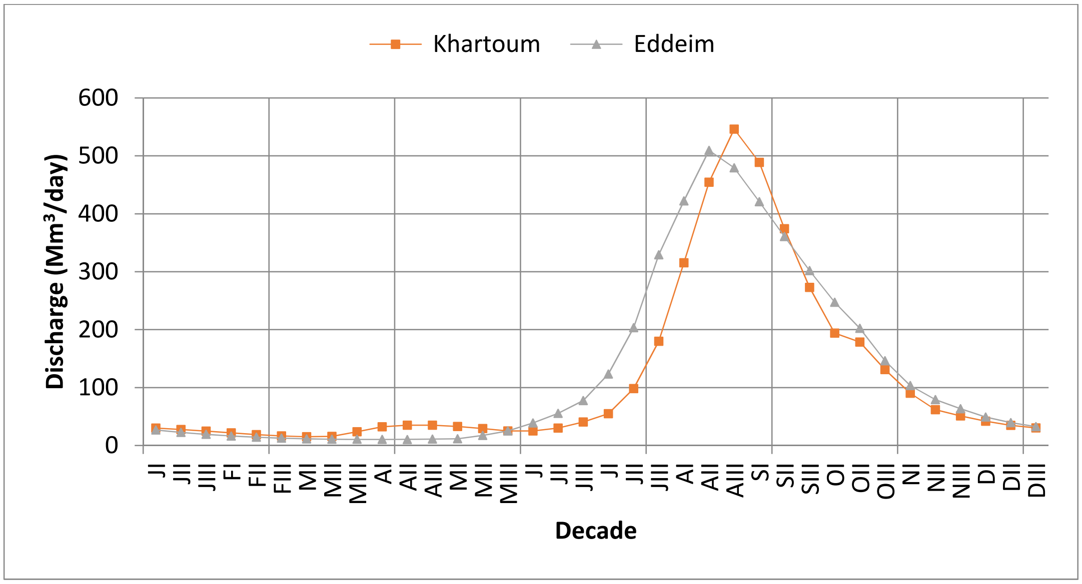


Figure 5: Long term flow hydrograph of Khartoum versus Eddeim (1965-2015)

Using the available validated data sets i.e. water levels and discharges to regenerate the rating curves for certain years e.g. 1988 and 1998 as representatives of high flow years, 1972 and 1984 as representatives of low flow years and 1980 as a representative of normal years, Figures 6-7. It was noticed that the constructed rating curves have formed a loop-shaped, Figure 8. Theoretically, such Q-H relationships may be caused by one of the following phenomena:

- rising or falling stages
- changes in cross-sectional area
- changes in vegetation
- backwater effects

According to the author, the above mentioned phenomena are highly obvious in Khartoum station mainly the rising and falling stages due to flood wave. Also, the changeable behaviour of the river bed at this location with respect to the flood level and the amounts of carried sedimentation (morphological changes) is clearly marked. It is to be taken into account that two third of the bed load at Khartoum station is silt and clay (clay is less than 10%) while the remaining percentage is considered sand (HRC, 2012). This is in contrast to situations when the river bed is rocky as the case of Eddeim gauging station, Figure 9.

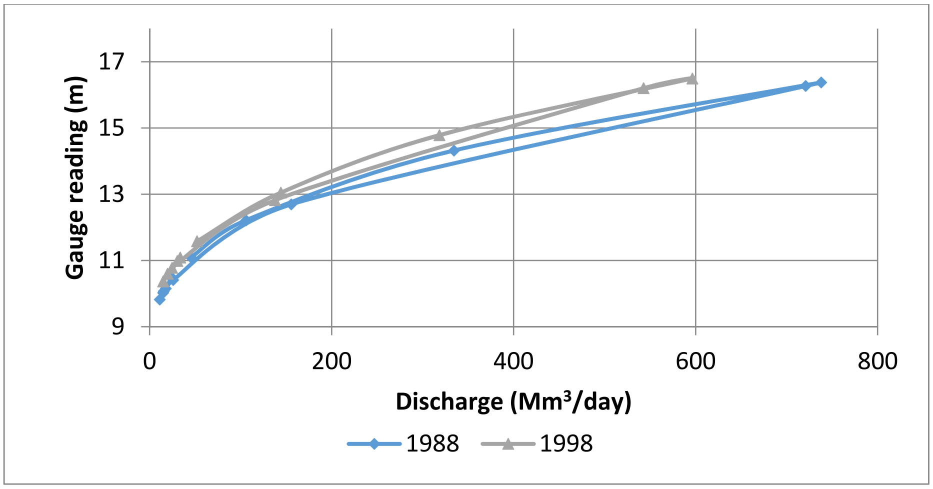


Figure 6: Generated rating curves at Khartoum for high flow years

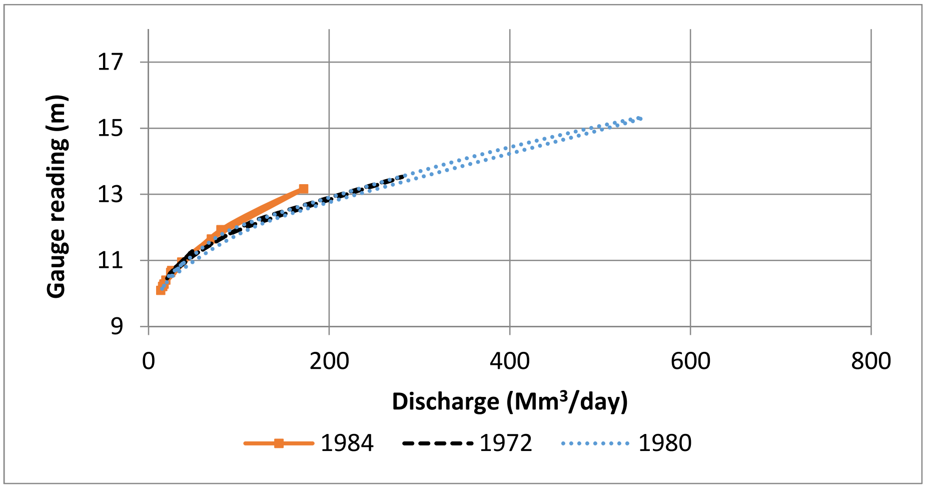


Figure 7: Generated rating curves at Khartoum for low flow and normal years

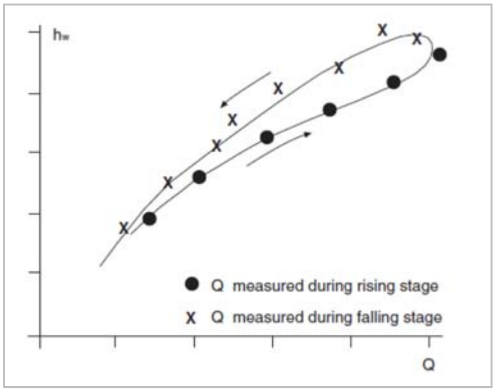


Figure 8: Sketch of a loop rating curve (Boiten, 2003)

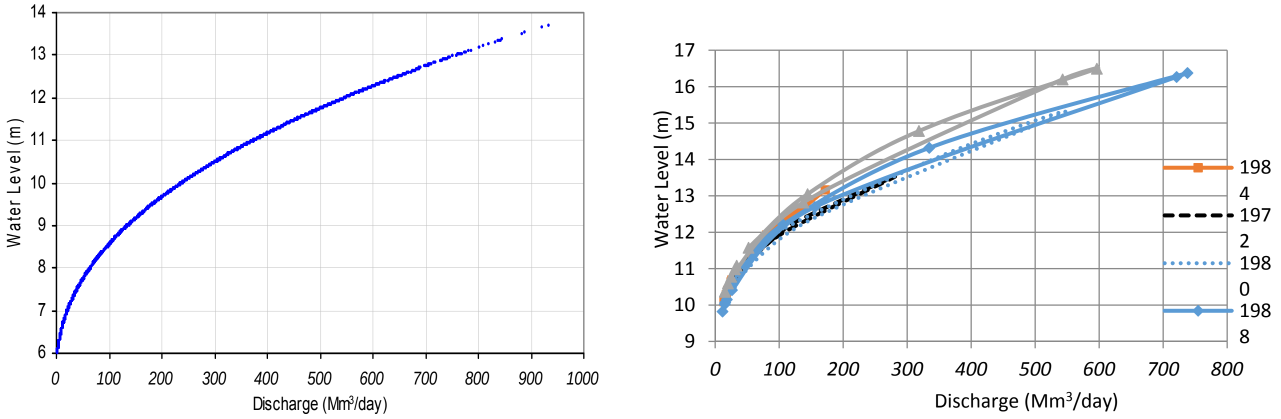


Figure 9: Rating curves of Eddeim (on the left) and of Khartoum (on the right)

<u>Testing Khartoum data against upstream gauging station</u>

Sennar dam is located 350 Km upstream Khartoum. It represents good selection to check Khartoum data against Sennar dam downstream releases. Thus, the following points should be highlighted and considered for the quick overview on the water balance of this reach:

1. The contribution of the two rivers Dinder and Rahad (excluding the diverted water to Rahad scheme which is nearly about 0.7 BCM).
2. Abstractions to meet irrigation requirements along this reach are estimated at around 1 billion m^3/yr for the period 1972-2000 (Mekawi, 2005) and 1.4 for the period 2001-2015 (Lahmeyer International, 2013).
3. Conveyance losses in the reach; the annual rainfall decreases from 455 mm at Sennar, to 328 mm at Wad Medani to 150 mm at Khartoum. In this reach of 350 km in length, the average depth of 311 mm and 2280 mm/yr can be used for rainfall and evaporation, respectively. Assuming an average width of the river of 800 m (Shahin, 1985), the water loss becomes 0.55 billion m^3/yr.
4. Surface runoff contribution which can be represented by Gezira scheme drain within this reach (estimated flow is about 0.25 billion m^3/yr).

The simple form of Sennar-Khartoum water balance can appear as follows:

$(Q_S + Q_{Din} + Q_{Rah}) - (A_b + E_L - R) = Q_{Kh}$

Where:

Q_S = flows at downstream Sennar dam, Q_{Din} = flows at Gwasi station, Q_{Rah} = flows at El Hawata station
Q_{Kh} = flows at Khartoum station
A_b = Abstraction by irrigation schemes within the river reach
E_L = Evaporation
R = Runoff from catchment between upstream and downstream gauging sites

Carrying out the water balance of the reach Sennar - Khartoum on annual basis and considering for outliers (years 1984, 1988, 1998 and 2015), it is proved that the balanced flows calculated at Khartoum are underestimated by 5.3 % on average in comparison with the observed total flows. This is for the period 1972 to 2015 as flow records of Dinder (at Gwasi) and Rahad (at El Hawata) are available since 1972 onwards. Figure 10 previews the calculated annual flows at Khartoum gauging site in comparison to the available flow records. Excluding the outliers, the difference between the calculated flows and the available ones can be presented by Figure 11 which shows that the majority of the monitored flows at Khartoum are overestimated.

Furthermore, the annual flows at Khartoum are compared with one historical source (Shahin, 1985) and it is obvious that the records are overestimated by 3.9 BCM (~ 10%) on average for the period from 1965 to 1973. On the other hand, the overall difference is not significant when considering the long term flow record as adopted from Sutcliffe et al, 1999. Table 4 summarizes the different annual records of Khartoum as discussed here.

Table 4: Average annual flows of Khartoum in comparison with historical sources

Period	Annual yield (BCM)	Remarks
1965-1973	38.5	Shahin, 1985
	42.4	This current study
1961-1995	40.199	Sutcliffe, 1999
1965-2015	42.8	This current study

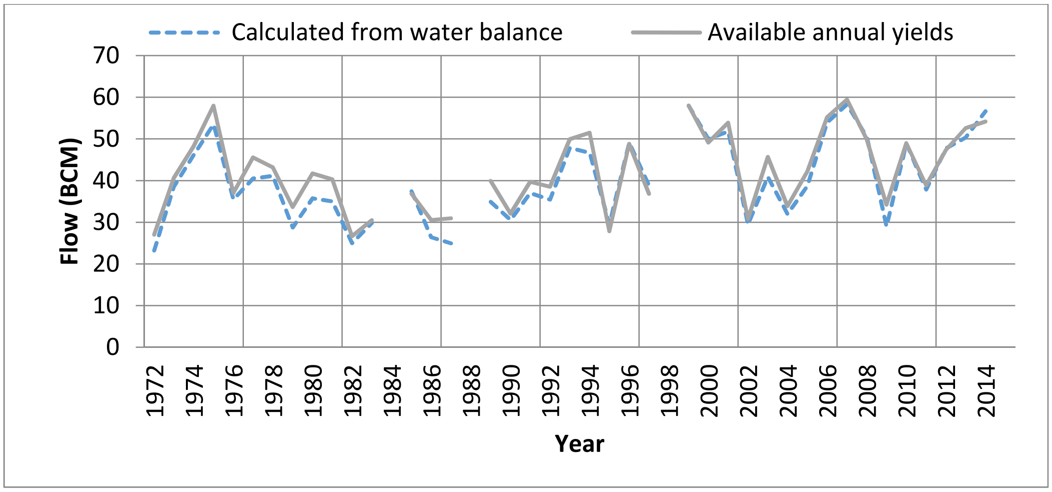


Figure 10: Annual Blue Nile River flows at Khartoum

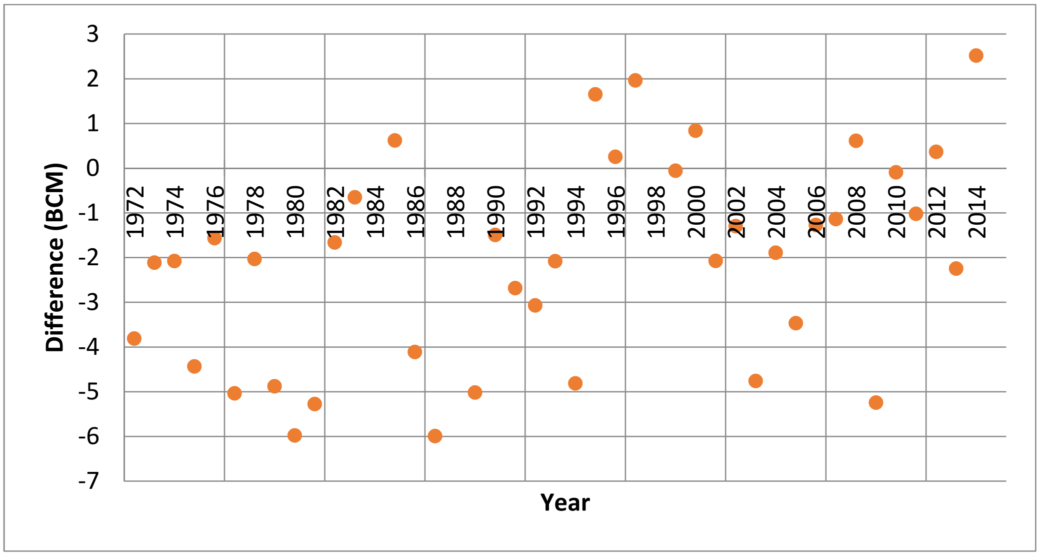


Figure 11: Difference between calculated flows at Khartoum and available records

Simulation of Khartoum data sets using RIBASIM software

RIBASIM was applied to generate the flows (on 10-day time step) over the period 1972-2015 at key stations under investigation. The overall performance of the model for simulating flows has been assessed using the Root Mean Square Error (RMSE) and the Nash–Sutcliffe model efficiency coefficient (NSE). RMSE is computed as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Q_{sim}-Q_{obs})^2}{n}}$$

Where:
Q_{sim} = simulated flow (m^3/s)
Q_{obs} = measured flow (m^3/s)
And NSE is derived as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model})^2}{\sum_{i=1}^{n}(X_{obs,i} - \overline{X_{obs}})^2}$$

Table 5 below summarizes the obtained records of the RMSE and NSE:

Table 5: Calculated values of RMSE and NSE

Station	**RMSE (m^3/s)**	**NSE (%)**
Roseires downstream	373.4	0.95
Sennar downstream	414.5	0.96
Khartoum	626.1	0.88

RIBASIM simulations on 10-day time step showed that there is a marked underestimate by about 9% for years of low yields at Khartoum station. Selected examples of the observed flows versus the simulated ones (dry years) are given by Figure 12.

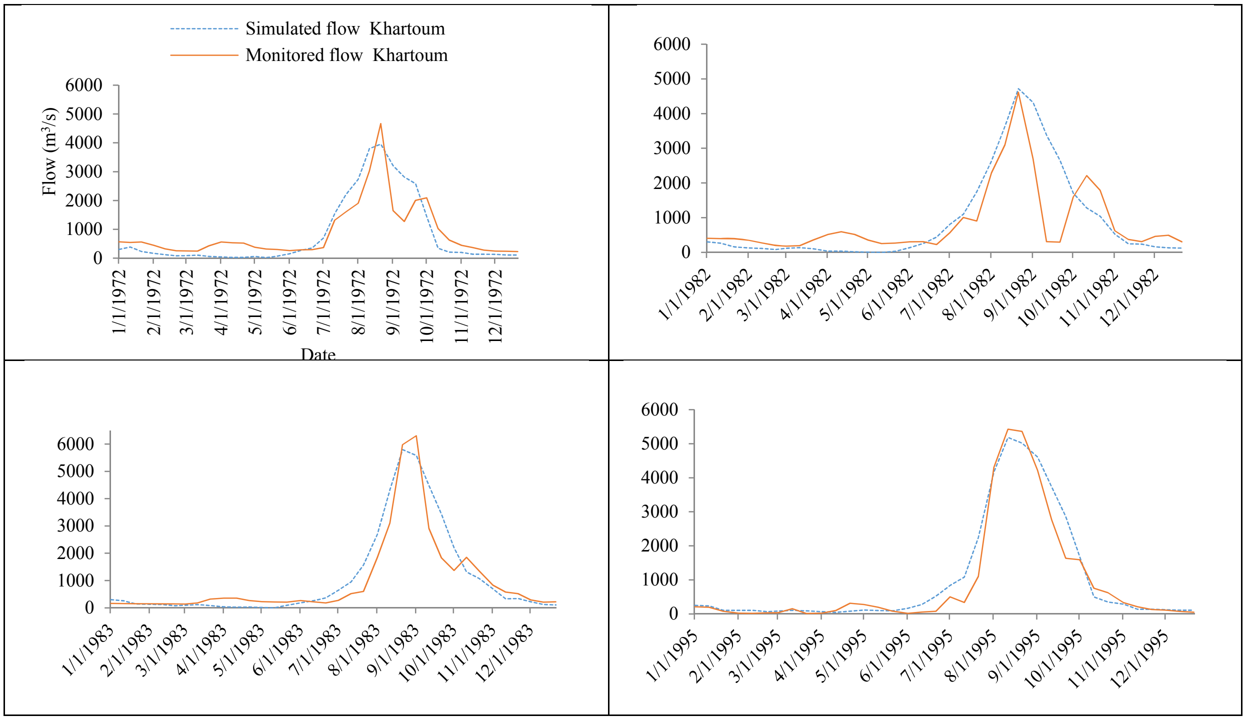


Figure 12: Observed versus simulated flows at Khartoum station for years of low yields

Vice versa, it was observed that there was an overestimate by 8% in years of high flows at Khartoum station. Selected examples of the observed flows versus the simulated ones (wet years) are given by Figure 13. The recorded overestimate and underestimate are average values around which records fluctuate. Although data inputs (inflows and abstractions) on 10-day time step were also applied for simulating the upstream gauging stations (Roseires d/s and Sennar d/s), these observations were not witnessed in both sites. Moreover, average records of operation rules of both reservoirs was adopted in RIBASIM simulations. However, one can observe that actual operation rules in dry and wet years were not fully accounted for in the model.

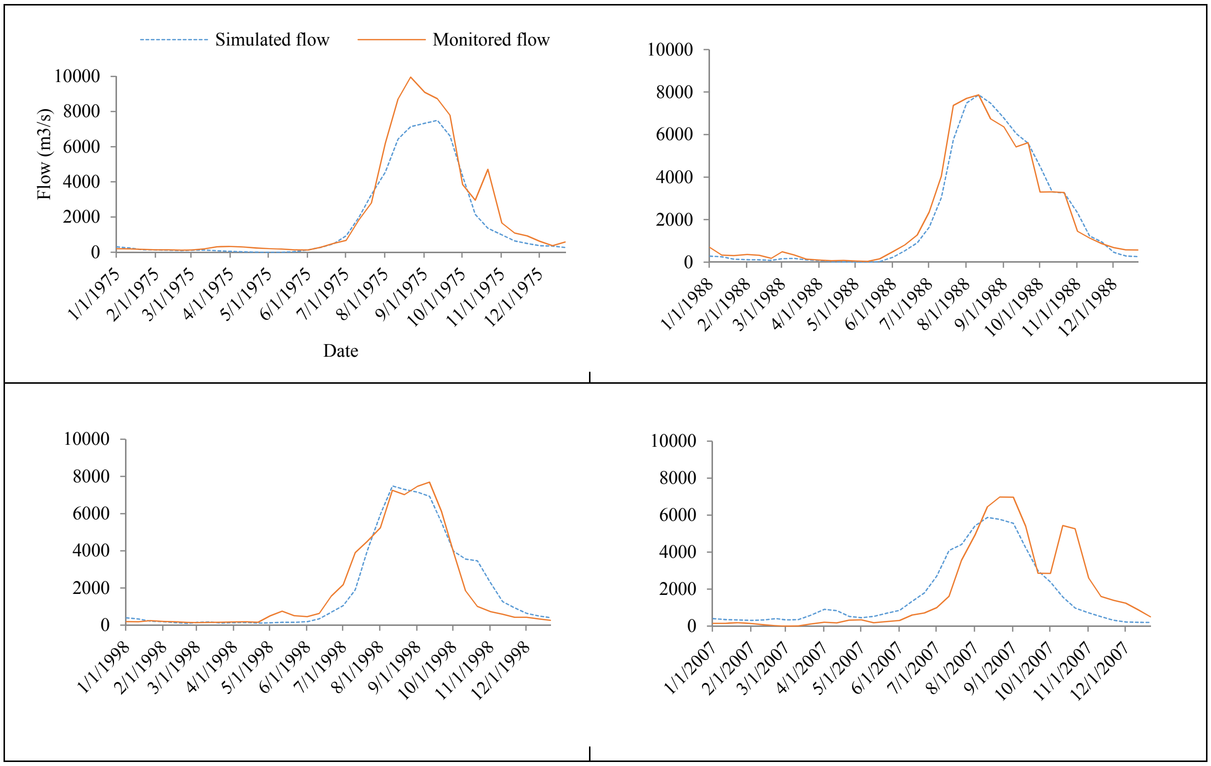


Figure 13: Observed versus simulated flows at Khartoum station for years of high yields

4. CONCLUSIONS AND RECOMMENDATIONS

It can be concluded that:

1. The annual flows are almost correctly calculated in the reach from Eddeim to Sennar dam. No doubt the operation rules of the two dams along the reach give a very good control and that is reflected in the quality of the calculated flows. However; few years obviously seem to be problematic and should be revised. This is reflected by the good values as given by adopted performance indicators (RMSE and NSE).
2. Testing of the time series of the annual yields at Khartoum (1965-2015) has shown that the trend is not significant. This is not valid for the time series of the 10-day average discharges.
3. After the high flooding of year 1988 there is a marked rise in the river bed level. Such morphological changes have to be considered carefully in establishment of rating curves.
4. In comparison with historical sources, Khartoum flows were found to be overestimated by 9.4% (1965 - 1973). One can not draw concrete conclusion in comparison with Sutcliffe (1961-1995) as the duration of provided hydrological data is different from the current work (1965-2015).
5. Taking into consideration errors in current metering (± 2.5%), the expected human errors in conducting flow measurements, and the limited number of measurements at the measuring site one can conclude that

overestimation in Khartoum flows by 5.3% over the investigated period can be considered realistic. However, RIBASIM simulations results show clear overestimate by 8% and underestimate by 9% in years of high and low flows, respectively.

6. The reliability of the flows at Khartoum is to some extent limited and their accuracy is subjected to the quality of established rating curves and the lack of discharge measurements throughout the year. Also, such uncertainties are sometimes attributed to reliability of upstream stations in some years of high or low flows.

The following points are recommended:

1. More attention has to be paid to the number of flow measurements and corresponding constructed rating curves considering morphological changes of the river bed.
2. The triangle of downstream Jebel Aulia dam, Khartoum and Tamaniat should be carefully investigated and it could also be a very good check for the flows at Khartoum.
3. Location of Khartoum station has changed several times in the last two decades, hence close observations are of utmost importance for reliable flow monitoring.

5. REFERENCES

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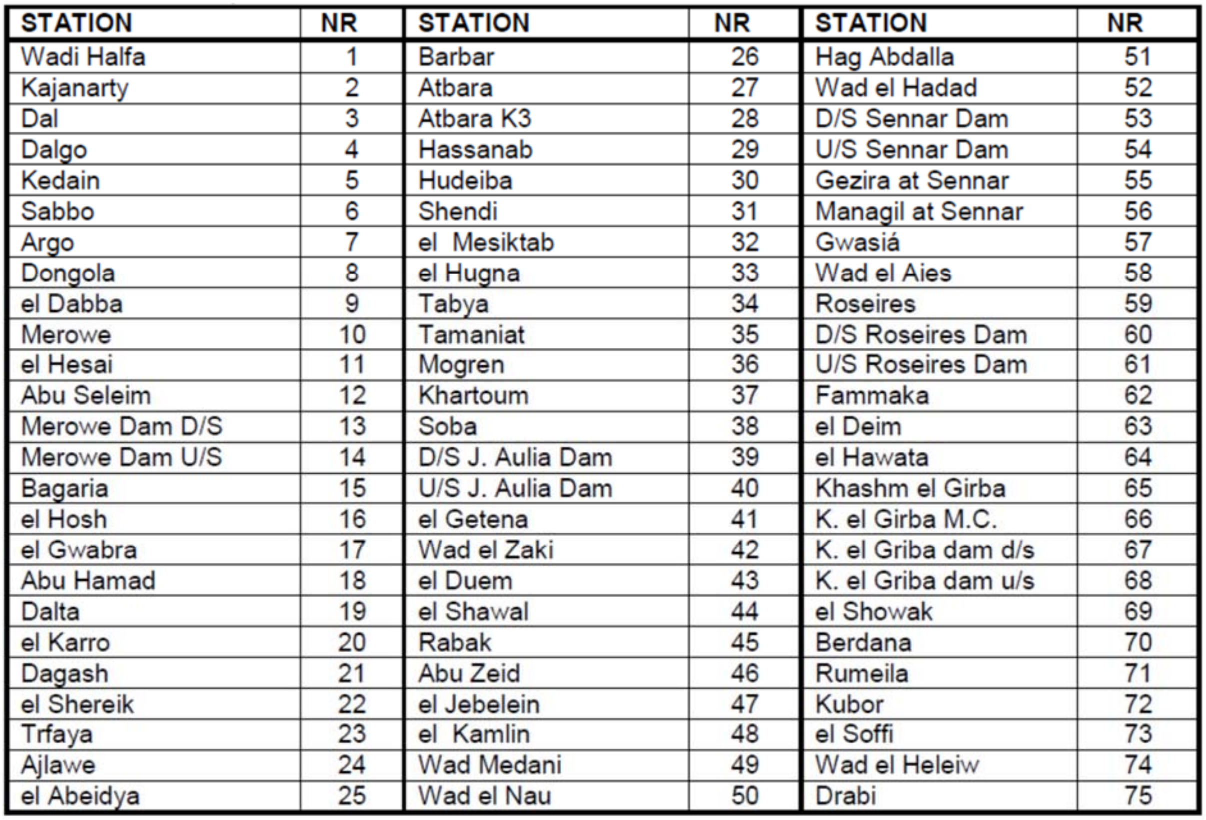
Annex A: Stations of hydrometric network in Sudan, SWECO International (2014)



STATION	NR	STATION	NR	STATION	NR
Wadi Halfa	1	Barbar	26	Hag Abdalla	51
Kajanarty	2	Atbara	27	Wad el Hadad	52
Dal	3	Atbara K3	28	D/S Sennar Dam	53
Dalgo	4	Hassanab	29	U/S Sennar Dam	54
Kedain	5	Hudeiba	30	Gezira at Sennar	55
Sabbo	6	Shendi	31	Managil at Sennar	56
Argo	7	el Mesiktab	32	Gwasiá	57
Dongola	8	el Hugna	33	Wad el Aies	58
el Dabba	9	Tabya	34	Roseires	59
Merowe	10	Tamaniat	35	D/S Roseires Dam	60
el Hesai	11	Mogren	36	U/S Roseires Dam	61
Abu Seleim	12	Khartoum	37	Fammaka	62
Merowe Dam D/S	13	Soba	38	el Deim	63
Merowe Dam U/S	14	D/S J. Aulia Dam	39	el Hawata	64
Bagaria	15	U/S J. Aulia Dam	40	Khashm el Girba	65
el Hosh	16	el Getena	41	K. el Girba M.C.	66
el Gwabra	17	Wad el Zaki	42	K. el Griba dam d/s	67
Abu Hamad	18	el Duem	43	K. el Griba dam u/s	68
Dalta	19	el Shawal	44	el Showak	69
el Karro	20	Rabak	45	Berdana	70
Dagash	21	Abu Zeid	46	Rumeila	71
el Shereik	22	el Jebelein	47	Kubor	72
Trfaya	23	el Kamlin	48	el Soffi	73
Ajlawe	24	Wad Medani	49	Wad el Heleiw	74
el Abeidya	25	Wad el Nau	50	Drabi	75